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ADVANCED MATERIALS ASPECTS OF CONCURRENT ENGINEERING

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Unique opportunities are offered for new devices and systems through the use of advanced materials, such as composites, ceramics, and intermetallics. Concurrent engineering approaches to the use of these materials are key to assuring successful applications. Generic steps in concurrent engineering with special reference to advanced materials are reviewed. Examples are provided of intelligent processing and net-shape processing, which provide routes to more reproducible materials. It is anticipated that a wide range of DARPA applications will be affected by the approaches described here, including the metal-matrix composites model factory, composite hulls and chassis for lightweight ground vehicles, and the polymer composite submarine hull.

CONTENTS

FIGURES

I. INTRODUCTION

In a 1988 IDA report, concurrent engineering (CE) is defined as the following:

> Concurrent engineering is a systematic approach to the integrated concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the onset, to consider all elements ot the product life cycle from conception through disposal, including quality, cost, schedule, and user equipments.[1]

Other authors use slightly different terminology, for example, "concurrent design."[2] The common idea uniting the various approaches to this still-evolving theme is the simultaneous, or concurrent, participation by the diverse groups involved in the evolution of a product, from the definition of its use in both broad and specific terms to its design, manufacturing, assembly, packaging, marketing, and sale, as well as its operation, maintenance, repair, salvage, and disposal. Many of the analytical tools, data bases, and computer aids to support concurrent engineering still need to be developed.

Figure I-1 shows schematically the major elements of activity in concurrent engineering that take place before the concept of a factory for production is defined.

This report focuses on several important aspects of concurrent engineering that are in the mainstream of DoD interests in advanced materials. Concurrent engineering is pertinent, for example, to such important new programs as the Metal-Matrix Composite Factory. As will be evident, there are many gaps in our circuit diagrams for concurrent engineering of systems that will employ advanced materials in the future.

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1 R.I. Winner, J.P. Pennell, H.E. Bertrand, and M.M.G. Slusarczuk, *The Role of Concurrent Engineering in Weapons System Acquisition*, IDA Report R-228, Institute for Defense Analyses, Alexandria, VA, December 1988, p.2.

2 J.L. Nevins and D.E. Whitney, eds., *Concurrent Design of Products and Processes*, McGraw-Hill, New York, NY , 1989.

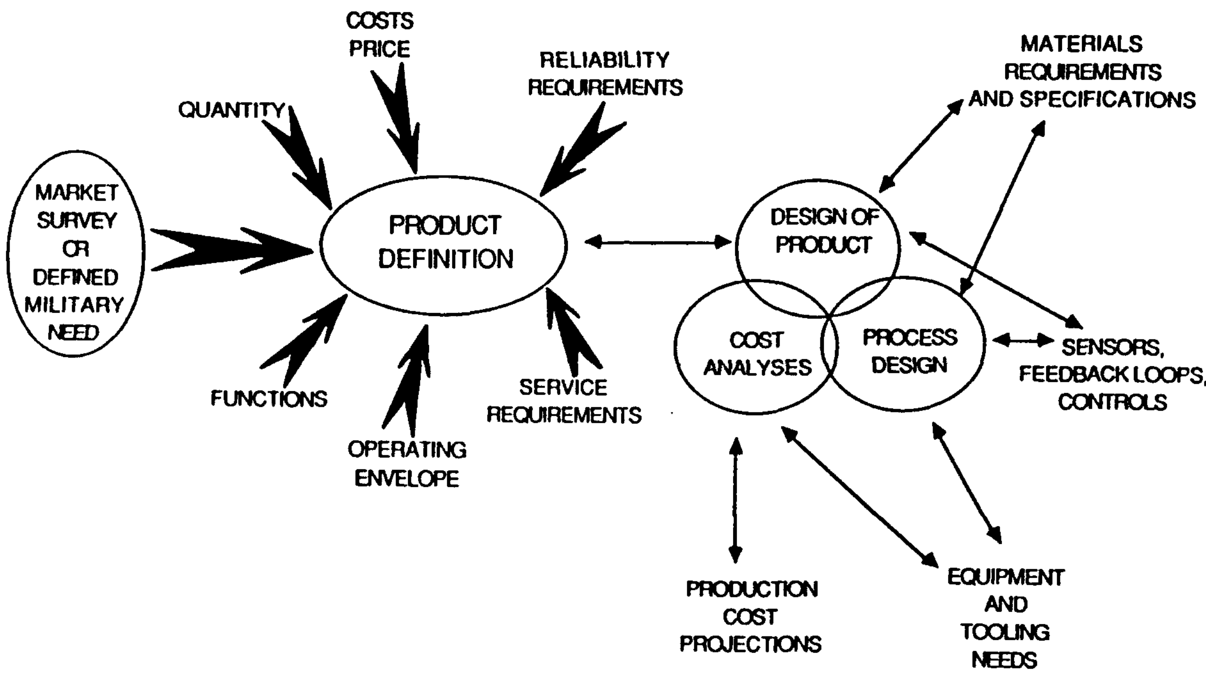


Figure I-1. Activity Flow in Concurrent Engineering Before Factory Productions

II. PROBLEMS AND OPPORTUNITIES

The past half century has seen an explosive proliferation of new materials in our society, spurred initially by World War II requirements. These needs, in areas such as weaponry, transportation, and communications, brought major advances in metallic alloys, plastics, and the beginnings of electronic materials. In subsequent years the demands of air and space technology, computers, and fast communication and control systems have brought exotic new classes of high-temperature materials such as ceramics, very lightweight and stiff composites, and ultra-small-scale tailored materials for information processing.

Unfortunately, the proliferation of new materials, with properties hitherto untenable, has not been matched by our ability to manufacture them reproducibly, with characteristics of high reliability and at reasonable cost. These inabilities in manufacturing of advanced materials have also been reflected in America's failure to achieve competitiveness in the manufacturing of advanced devices and systems. In this broader context, timeliness is of key importance. Figure II-1 summarizes the opportunities and the problems specific to advanced materials, and the diagram of Figure II-2 illustrates one of the key problems in advanced materials today--the lack of reproducibility. The development of the highest levels of performance, but with a wide scatter band in properties (A), is symptomatic of what has been the inability to identify and/or control the key variables in the structure, composition, and processing of materials. Faced with the choice of using a material with such a wide scatter band of properties against one with a much lower level of reproducible properties, the designer will choose the latter. The realistic aim is to approach a scatter band which does not achieve the highest level of performance--but is high--and shows a narrow scatter band (B), as indicated in Figure II-2.

For the DoD, special considerations exacerbate such problems. These are shown in Figure II-3, which describes some of the problems characteristic of high-value defense systems. A number of key approaches to address the problems of simultaneously increasing quality, reducing cost, decreasing development time, enhancing maintainability, and extending useful product lifetimes are shown in Figure II-4. Many of the approaches

THE OPPORTUNITIES

- ADVANCED MATERIALS, ESPECIALLY NEW CERAMICS, COMPOSITES, AND INTERMETALLICS, MAY PROVIDE NEW LEVELS OF PERFORMANCE FOR DEVICES AND SYSTEMS.

THE PROBLEMS

- LACK OF REPRODUCIBILITY
- LIMITED MANUFACTURING BASE
- DESIGN, INSPECTION, JOINING, REPAIR AND MAINTENANCE ARE KEY ISSUES
- HIGH COST

Figure II-1. Opportunities and Problems Represented by Advanced Materials

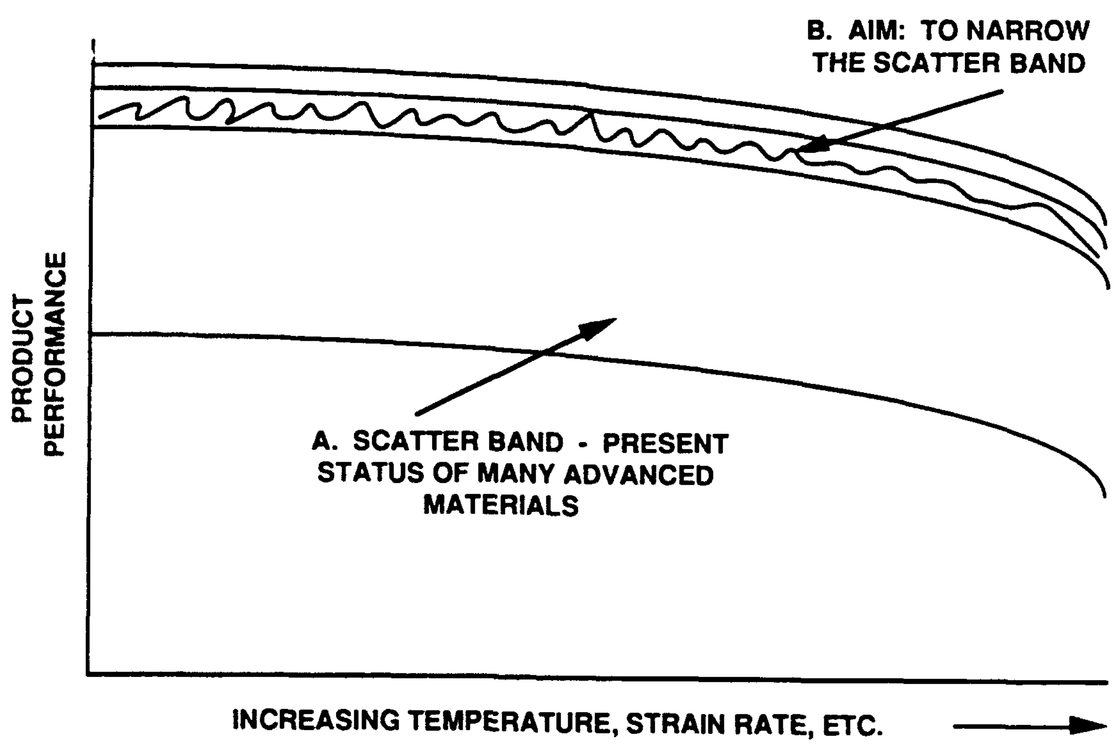


Figure II-2. Reproducibility of Many Advanced Materials

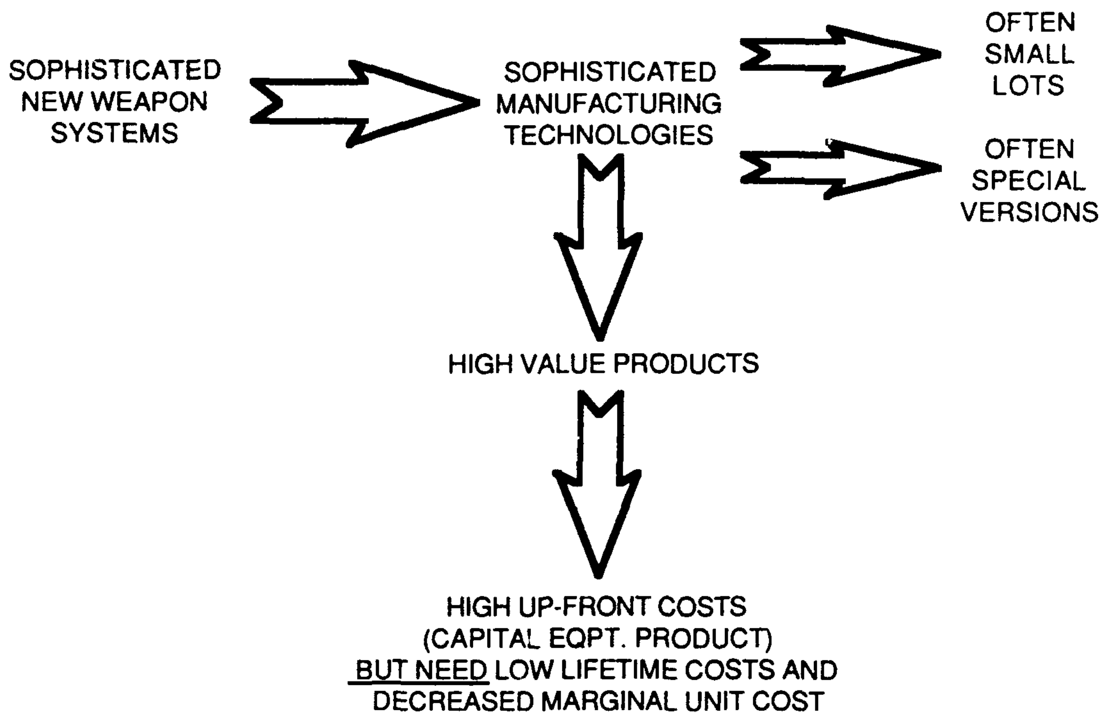


Figure II-3. Special DoD System Characteristics

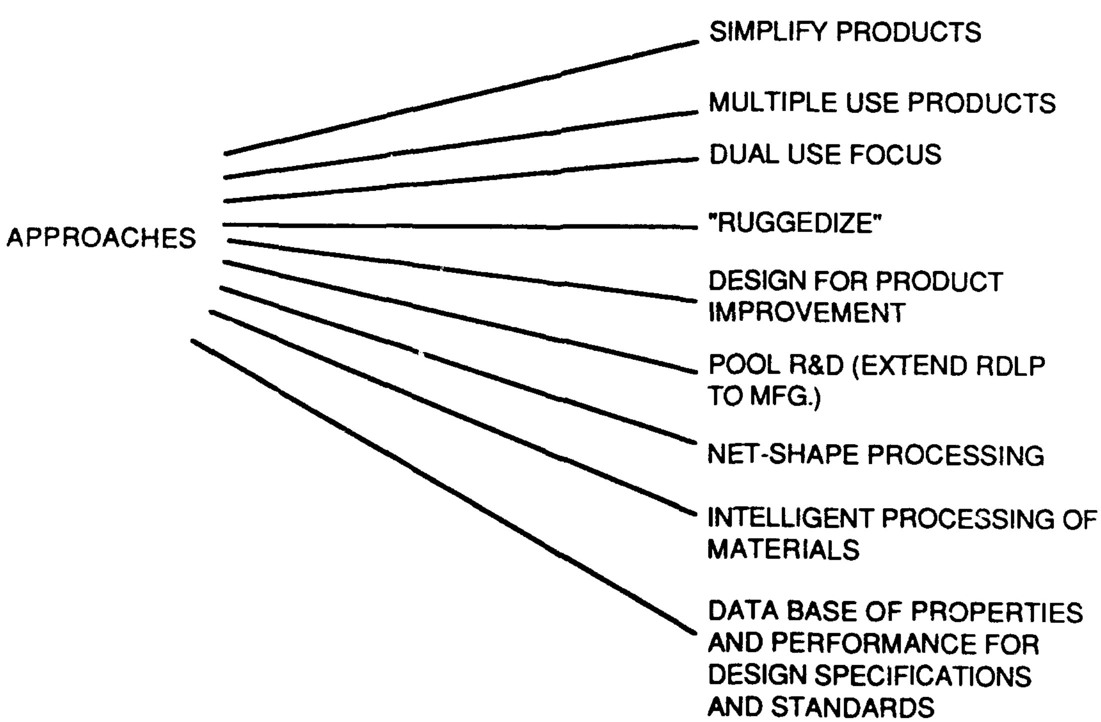


Figure II-4. Characteristic Concurrent Engineering Approaches

indicated in this figure are obvious, such as the simplification of products to reduce parts and ease manufacturability, and modular design for product improvement, which allows for simple upgrades of systems without gross redesign. Others, such as the pooling of research and development by companies that normally compete with one another, through vehicles such as research and development limited partnerships (RDLP), are not so obvious. Some approaches, such as the generation of data bases, may seem pedestrian, but are critical elements of concurrent engineering. For many kinds of advanced materials, reliable and/or comprehensive data bases are lacking. Several aspects of CE which are of special importance to the materials community will be described in the following sections. The benefits of judicious application of CE, and the penalties of "repairing in" quality and the other "ilities" are shown in Figure II-5. Here it is evident that although the initial costs of capital equipment, special sensors, etc., may be high in the example of a product which is made using CE principles, the cross-over in costs compared to a system engineered without CE occurs quite rapidly. The lifetime cost of ownership can be impressively conservative with CE, and added benefits would accrue when systems such as the B-52 airplane and the M-60 tank are used well beyond their predicted lifetimes of use. The return-on-investment can be measured by comparing the areas in the diagram, B/A, for a system designed with CE in mind versus one without. Other important factors to the user are the numbers of systems in operation, rather than down for repairs, whether one operates a B-52 fleet, a submarine fleet, or a taxi fleet, and customer dissatisfaction with delays.

An additional critical reason for employing CE at the outset of a product's life is indicated in Figure II-6. It shows the influence of each phase of the life cycle of a product on the final cost and illustrates that about 75 percent of the total cost of a product essentially accrues prior to full scale development! This curve does not indicate how much each phase costs, but rather how much influence each phase has on the final cost. Setting the stage early in the life cycle of a product for a high return-on-investment is clearly necessary.

Central emphasis should be made in concurrent engineering on a requirements-driven approach (Figure II-7). This means the definition of the load spectrum under which the system operates (electrical, mechanical, thermal, etc.) as a function of time, the environment in which the product lives, and related factors. Product and process requirements need to be similarly defined.

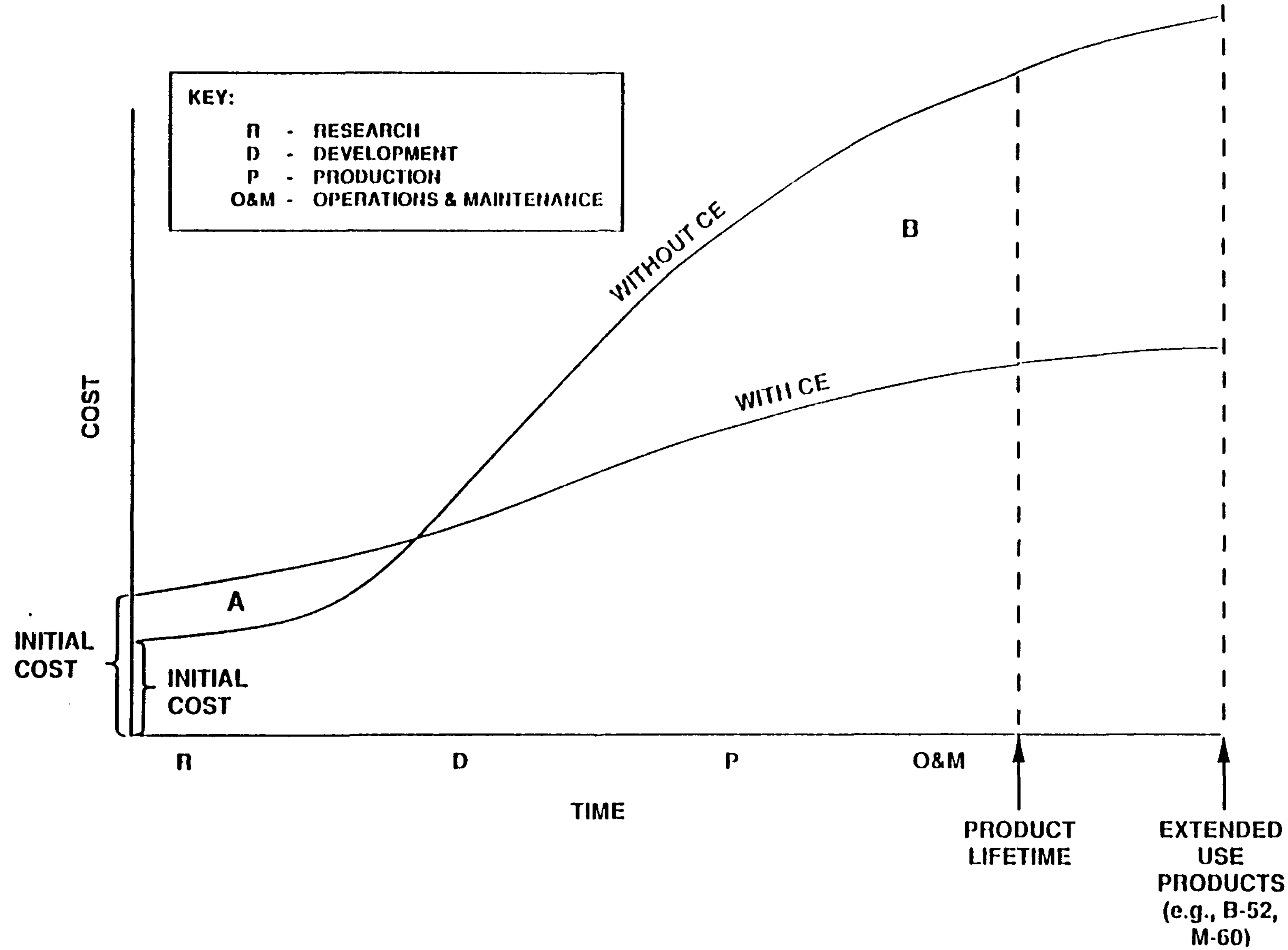
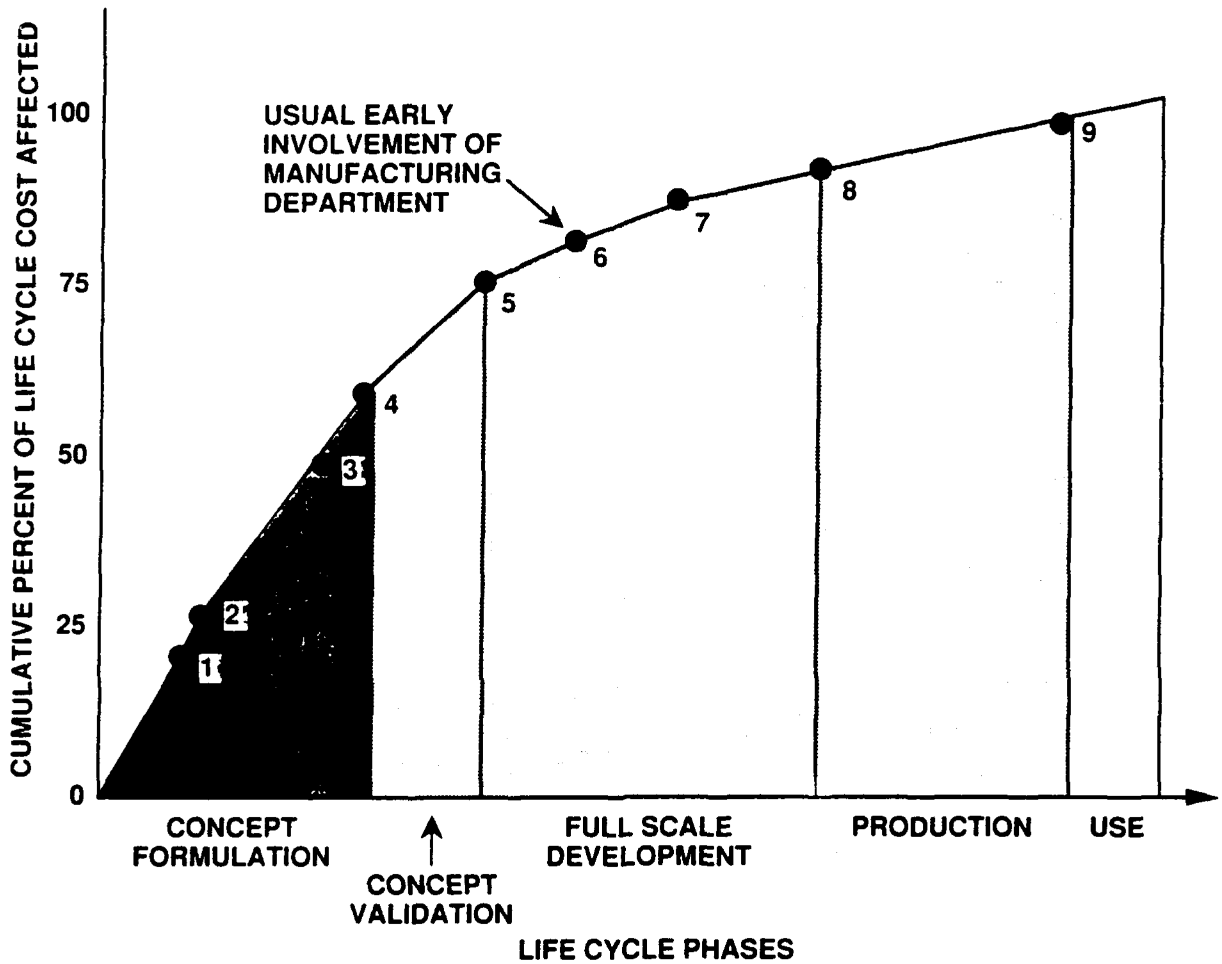


Figure II-5. Lifetime Costs of Systems With and Without Concurrent Engineering



1. DEFINE USE PATTERNS
2. DEFINE ALTERNATIVES
3. DEVELOP ALTERNATIVES
4. FREEZE SUBSYSTEMS
5. PROVE FEASIBILITY
6. PROVIDE PRELIMINARY DESIGNS
7. PROVIDE DETAIL DESIGNS
8. PROVIDE MANUFACTURING PLANS
9. PRODUCT

9-19-91-1M

Figure II-6. How the Life Cycle Cost of a Product Is Determined During Various Phases of Design. (From *Concurrent Design of Products and Processes*, by Nevins and Whitney, 1989)

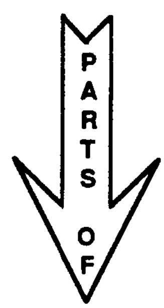
- MATERIAL PROPERTY REQUIREMENTS SHOULD REFLECT SPECIFIC DEVICE OR SYSTEM REQUIREMENTS AS THEY RELATE TO ITS "OPERATING ENVELOPE."
- PRODUCT AND PROCESS REQUIREMENTS WILL INDICATE WHAT TECHNIQUES OF MANUFACTURING ARE FEASIBLE (OR WHAT CHARACTERISTICS THEY SHOULD HAVE), HOW PRODUCTS SHOULD BE DESIGNED, HOW FACTORIES SHOULD BE LAID OUT AND OPERATED.

Figure II-7. Elements of a Requirements-Driven Approach

III. APPROACHES TO SOLUTIONS

By way of example, several attractive concurrent engineering approaches within the area of materials science and technology, are indicated in Figure III-1. During the past several decades, many net-shape processing concepts have simplified materials processing. In a simplistic sense, fewer processing steps mean fewer points in the flow chart where controls must be exercised. In addition, some new, and some older nondestructive evaluation methods have been employed in real-time sensing for process control. As a third example, consider new manufacturing concepts such as the Lanxide system of material processing (Figure III-2) which embodies a molten infiltration system to make in-situ a complex composite, for example, a cermet. Figure III-3 is an example of how a powder metallurgy part is made by conventional means, and how it might be simplified by a net-shape process called Liquid Dynamic Compaction. The projected benefits of net-shape processing are indicated in Figure III-4, and range from the elimination of intermediate equipment and tooling costs, decreased labor and energy costs, and so on.

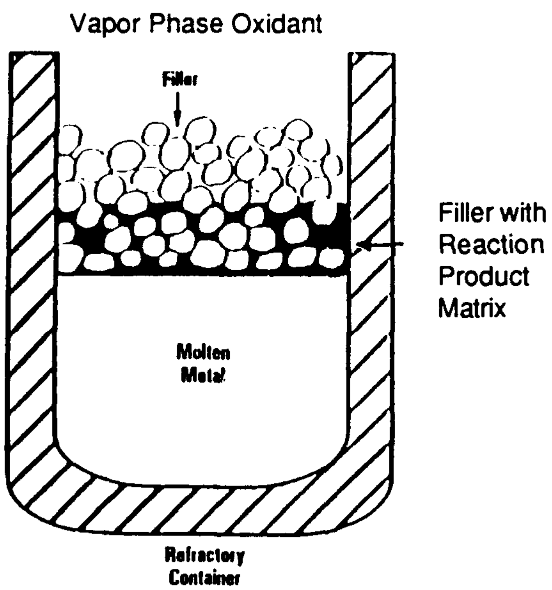
- SIMPLIFIED, NET-SHAPE, LOWER-COST PROCESSING
- IN-PROCESS AUTOMATED NDE FOR SENSING AND CONTROL
- NEW MANUFACTURING CONCEPTS



- COMPREHENSIVE CONCURRENT ENGINEERING APPROACH

Figure III-1. Some Approaches to Solutions

COMPOSITE
FORMATION



COMPOSITE TECHNOLOGY--
GENERAL CHARACTERISTICS

- Directed matrix growth around filler
- Spaces filled by reaction product matrix
- Filler material not displaced during matrix formation
- Wide range of filler materials and geometries, e.g.,--
  - Fibers
  - Whiskers
  - Particles

Figure III-2. The LANXIDE Process

CONVENTIONAL

RAW MATERIALS
REFINE POWDERS
PURIFICATION
CANNING
HOT EXTRUSION
DE-CANNING
MACHINING
JOINING
FINISHED PART

NET-SHAPE

RAW MATERIALS
REFINE AND PURIFY POWDERS
LIQUID DYNAMIC COMPACTION OF FINISHED PART

Figure III-3. Process Simplification by Net-Shape Forming

- ELIMINATE INTERMEDIATE TOOLING COSTS
- ELIMINATE INEFFICIENT, EXPENSIVE INTERMEDIATE EQUIPMENT
- ELIMINATE INTERMEDIATE LABOR COSTS
- ELIMINATE INTERMEDIATE ENERGY COSTS
- ELIMINATE SCRAP
- AVOID HIGH MACHINING OR GRINDING COSTS
- HIGH (LIKELY) COST OF NET-SHAPE CAPITAL EQUIPMENT MAY BE OFFSET BY ELIMINATION OF NEED FOR INTERMEDIATE EQUIPMENT

Figure III-4. Benefits of Net-Shape Processing

The specific steps that are necessary for generic processing control are indicated in Figure III-5. It should be stressed that four things must precede the design of the manufacturing process. These include: first, the definition of the product and its related performance and property requirements; second, the design of the product; then, a cost analysis of competing materials and processing methods; finally, these steps are followed by the selection, based on the foregoing, of the material(s) and processing method(s) to be employed.

- DEFINE PRODUCT AND PROPERTY REQUIREMENTS
- DESIGN PRODUCT
- PERFORM COST ANALYSES BASED ON COMPETING MATERIALS AND PROCESSING METHODS
- SELECT THE MATERIALS AND PROCESSING METHOD TO BE EMPLOYED
  (1) Design the manufacturing process
  (2) Simulate the process with analytical modelling techniques
  (3) Perform sensitivity analysis (or devise an interaction matrix, etc.) to determine major variables which govern levels of properties and reproducibility
  (4) Determine which variables and items are to be controlled and limits (windows of acceptance)
  (5) Decide on sensors (type, sensitivity, etc.) or develop them
  (6) Design control algorithms based on (2) and (3)
  (7) Control of equipment and processing conditions in real time through feedback from (5)

Figure III-5. Generic Processing Control Steps

Once the materials and processing methods are chosen, a series of steps (as indicated in Figure III-5) is followed to address the issues of modelling, sensors, and controls. Modelling variables typically include heat flow, thermal gradients, mixing parameters, etc. An in-depth discussion of modelling will not be given here. Suffice to say, however, that it is a first step to identification of the variables which control the properties of a product, the reproducibility of those properties, and subsequent product performance. It should be stressed at this point that it is not useful or economically feasible to sense and control all of the variables involved in processing. This is one of the reasons why process simplification is so important. Item (4) in Figure III-5 cites the limits to which things must be controlled. It is obvious that, the more forgiving a processing parameter, the wider the window of acceptability, and this often results in less stringent demands in the sensing system, and lower costs. Faster production rates may also be possible.

In the broadest interpretation, a sensor detects or measures a chemical or physical event and converts the signal received to another kind of signal, generally electrical. Figure III-6 lists typical kinds of signals that are emitted, and examples of these. Figure III-7 illustrates examples of signals, effects, and some transducers based upon those effects. What is sought in the special sensors that might be used for process control are early detections of warning signals. These are indications that the existing processing conditions would lead to microstructural and/or property conditions of the finished product that would not fall within the windows of acceptability. For example, a small change in electrical conductivity might indicate that dislocations or other defects are being introduced into the material during processing--too many of these could mean that the part will be scrapped. Because the measurements are to be made in a manufacturing environment, the detections of signals on the production line must be done in real time, that is, early enough to transfer the signal through a feedback loop to compare with the standards of acceptability, and to correct the processing conditions rapidly to bring the system back within the window of acceptability. All this should be done without hampering the rate of production of parts!

Other sensor requirements for process control are listed in Figure III-8. As is evident, the requirements are very stringent and demand imagination on the part of the sensor designer. Because of the general requirement that the sensor be nondestructive, issues such as the control of microstructural or compositional features on the nanoscale level of new classes of materials are especially challenging. At present, many known

Radiant signals	Intensity, wavelength,polarization, phase, reflectance, transmittance,
Mechanical signals	force, pressure, torque, vacuum, flow, volume, thickness,mass, level, position, displacement, velocity, acceleration, tilt, roughness, acoustic wavelength and amplitude
Thermal signals	Temperature, heat, specific heat, entropy, heat flow, voltage, current,
Electrical signals	charge resistance, inductance, capacitance, dielectric constant, electric polarization, frequency, pulse duration
Magnetic signals	Field intensity, flux density, moment, magnetization, permeability,
Chemical signals	composition, concentration, reaction rate, toxicity, oxidation-reduction potential, pH, pollutants

Figure III-6. Six Groups of Signals with Examples (From: K.S. Lion, "Transducers: Problems and Prospects," *IEEE Trans.* IECI-16, No. 1, July 1969)

In \ Out	Rad.	Mech.	Thermal	Magn.	Chem.	Electrical	Transducers
Radiant						Photovoltaic effect Photoconductivity Photomagnetoelectric effect Photoemissive effect	Solar Cell Photodetector
Mechanical						Piezoelectric effect Piezoresistance Triboelectric effect	Piezotransistor Pressure Cell
Thermal						Seebeck effect Thermally sensitive resistivity Pyroelectric effect Thermodielectric effect	Thermocouple Thermoresistor
Electrical						—	
Magnetic						Hall effect Phys. magneto resistance Geom. magneto resistance Suhl effect	Hall plate Reproducing Head
Chemical						Galvanoelectric effect Electrolytic conductivity Chemoelectrification Impurity-sensitive resistivity	pH-meter Galvanic cell

Figure III-7. Physico-Chemical Effects and Representative Transducers. (From: National Materials Advisory Board, 1989, *On-Line Control of Metal Processing*, NMAB Report No. 444, Washington, D.C., National Academy Press)

REAL-TIME RESPONSE
ACCURACY
SENSITIVITY
RESOLUTION
DURABILITY
FLEXIBILITY
NON-PERTURBING
NON-INVASIVE (IF POSSIBLE)

} OVER A RANGE OF OPERATING CONDITIONS

Figure III-8. Sensor Requirements for Process Control

characterization methods for the latter materials, such as scanning transmission electron microscopy (STEM) and Auger electron spectroscopy (AES), are neither rapid nor nondestructive, nor amendable to the production line.

To further illustrate the complexity and challenge of controlling quality and reproducibility of some advanced materials, several examples are given below of variables that it may be of interest to sense and control in the future. Figure III-9 shows some of the variables of interest in ceramic composite processing. Figure III-10 goes into greater detail on the more general elements of composite materials. Here, we see three sets of factors which need to be addressed: control of the characteristics of the matrix materials, the fillers, and the composites themselves. But the criticality of the variables for the properties and performance of interest should be determined before deciding which of the variables--and to what extent--need to be sensed and controlled.

A major point which must be made here is that our understanding of the key variables for control of quality and reproducibility of many advanced ceramic, intermetallics, and composite materials is progressing slowly, and data bases have not been well established. So, we can envision some of these concurrent engineering applications as case studies in progress. The situation in semiconductor materials is in better condition. In the example of gallium arsenide, the grown crystal itself is fairly close to device application without a lot of intervening processing steps. A flow chart for GaAs crystal growth is shown in Figure III-11. In this case, a computational approach has been applied to the

analysis of NIR (near infrared) transmission microsopy, which has allowed non-destructive quantitative semiconductor analysis with unprecedented resolution, sensitivity, and speed. High product quality and reproducibility are thereby assured.

- Temperature
- Pressure
- Density
- Pore Size
- Partial Pressures of Reactants
- Partial Pressures of By-Products
- Stoichiometry
- Matrix Structure
- Interface Structure and Bonding
- Reinforcement Size, Shape, Perfection, Distribution, and Orientation
- Residual Stresses

Figure III-9. Some Variables of Interest in Ceramic Composites

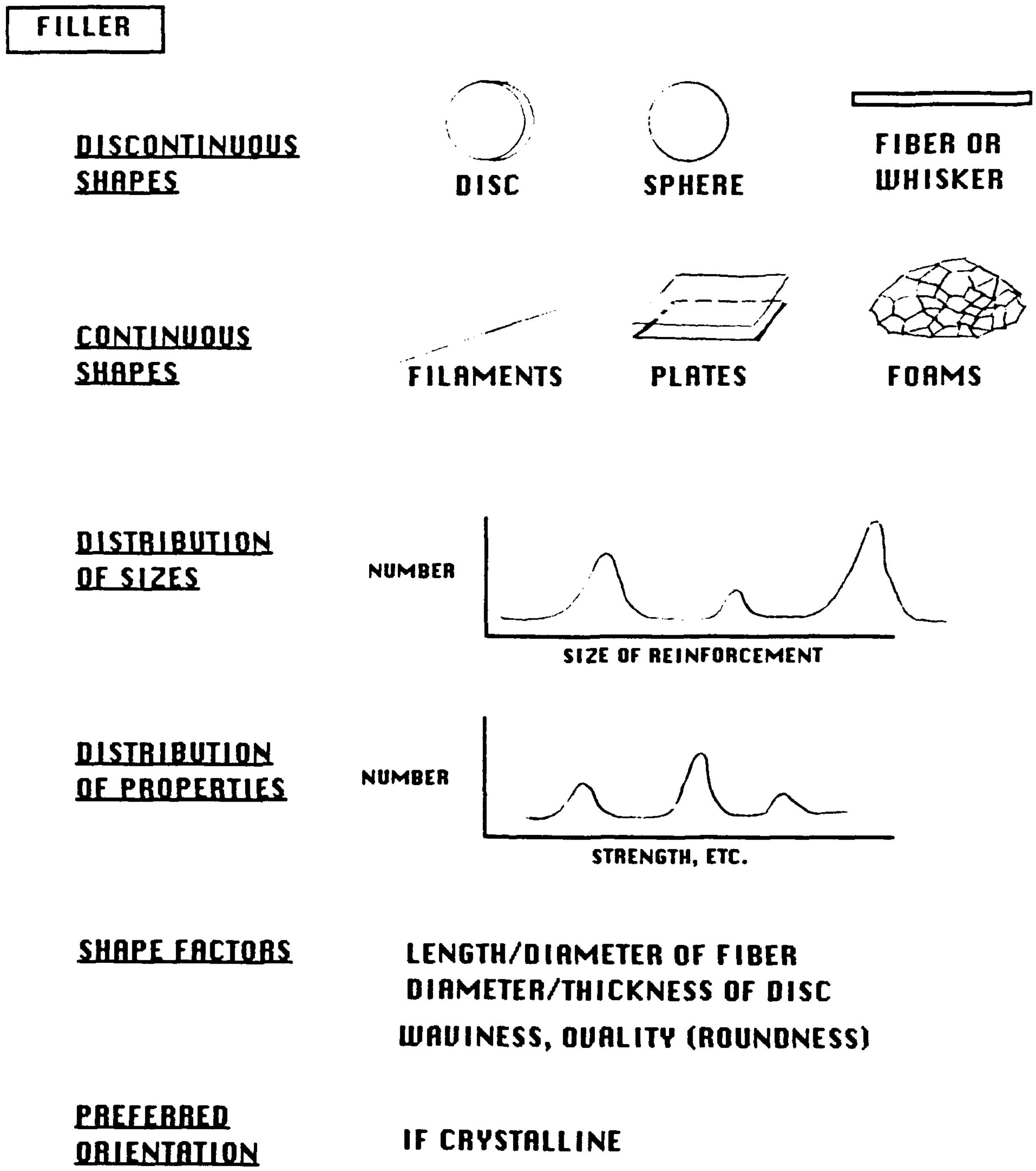


Figure III-10a. Some Complexities of Composites

MATRIX

- MIXING UNIFORMITY
- COMPATIBILITY WITH FILLER
  - THERMAL EXPANSION COEFFICIENTS
  - CHEMICAL REACTIVITY
- ANISOTROPY

COMPOSITE

INTERFACES AND SURFACE PREPARATION

BONDING OF FILLER AND MATRIX

MORPHOLOGY AND ANISOTROPY OF COMPOSITE

PROBABLY DIRECTIONAL PROPERTIES

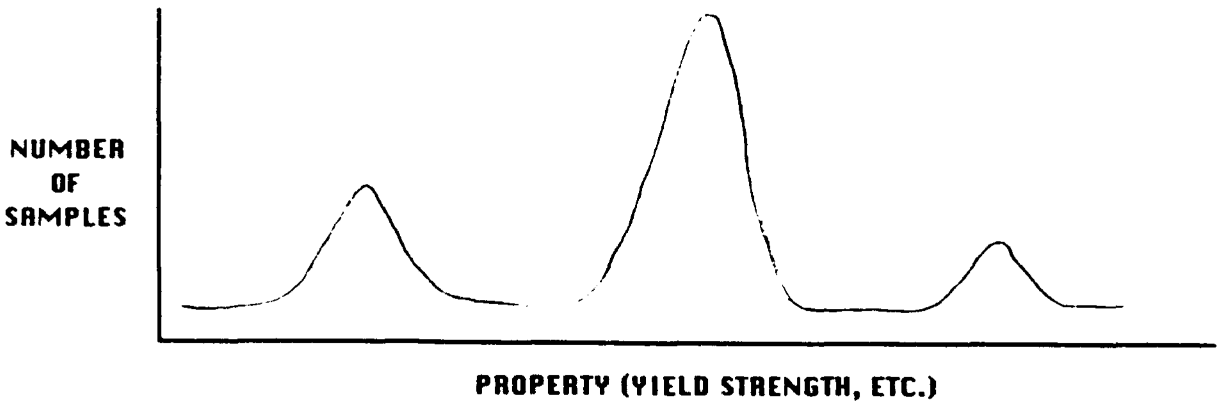


Figure III-10b. Some Complexities of Composites (continued)

COMPOSITE (CONTINUED)

JOINING	
REPAIR	
VOIDS	INCOMPLETE BONDING, GAS EVOLUTION
RESIDUAL STRESSES	FILLER, MATRIX, COMPOSITE (ESPECIALLY THICK-SECTION)
FIBER BREAKAGE	DURING FORMATION OF FIBER, OR TOWS, AND DURING CONSOLIDATION
FAULTS	KINKS, ETC.
DESIGN ASPECTS	CANNOT SUBSTITUTE COMPOSITES FOR MONOLITHIC MATERIALS ON A ONE-FOR-ONE BASIS.

Figure III-10c. Some Complexities of Composites (continued)

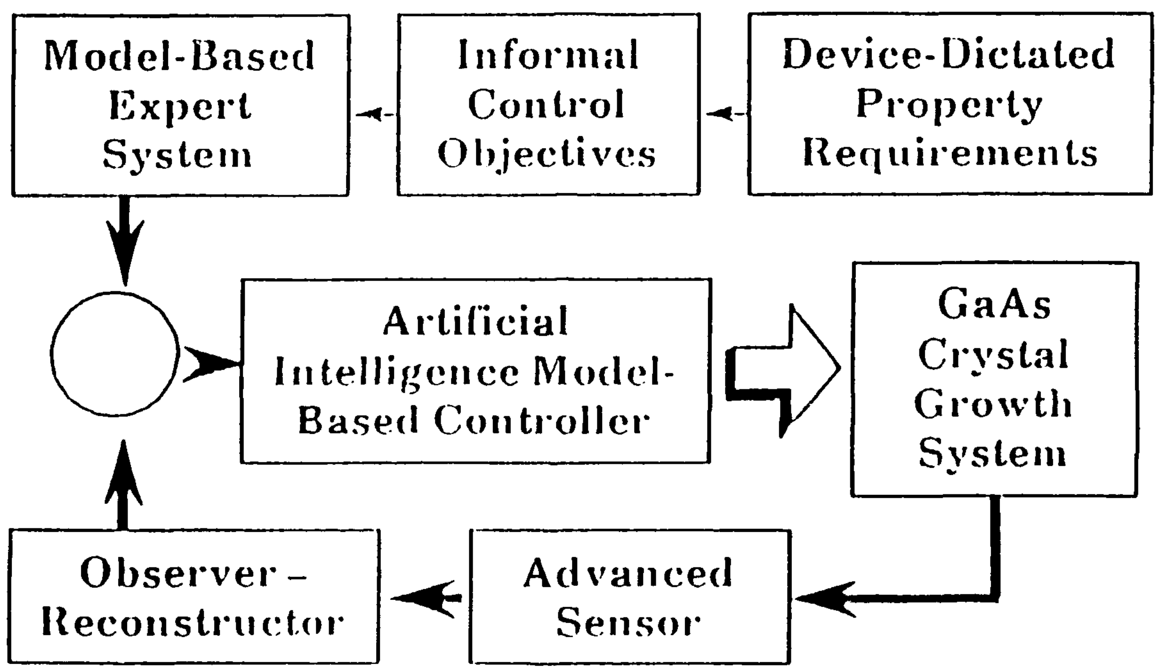


Figure III-11. On-Line Control of GaAs Crystal Growth (Courtesy of A.F. Witt, M.I.T., December 1990)

IV. SUMMARY

As indicated by the foregoing examples, the challenges of CE are indeed formidable. However, the pay-offs are not only attractive, but necessary to assure industrial competitiveness and a return to the high standards of product quality for which the United States was famous over many years.

Some of the issues that are of governing importance within this arena for fabricated materials are shown in Figure IV-1. These are self-explanatory. In the case of a finished product or a device, the nature of the issues is somewhat different, as indicated in Figure VI-2. Concepts of flexible manufacturing and just-in-time manufacturing need to be more broadly employed by organizations which deal with products containing advanced materials. Finally, the program benefits for both producers and consumers can be "taken to the bank," as indicated in Figure IV-3.

- HIGH QUALITY STARTING CONSTITUENTS
- FORGIVING MATERIAL (RANGE OF FABRICATION)
- NET-SHAPE FORMABILITY
- REPRODUCIBILITY
- EASE OF PURIFICATION
- UNDERSTANDING OF MICROSTRUCTURE/PROCESSING/PROPERTIES
- UNDERSTANDING OF CONTROLLING VARIABLES FOR PROPERTIES
- COMPREHENSIVE DATA BASE OF PROPERTIES
- EQUIPMENT COSTS
- FABRICATION COSTS

Figure IV 1. Issues for Fabricated Materials

- SIMPLICITY
- ROBUSTNESS
- FEWER PARTS
- INTERCHANGEABILITY
- PROVISION FOR UPGRADE
- EASE OF ASSEMBLY
- EASE OF INSPECTION AND MONITORING
- CONSTRAINTS:
  - Is it amenable to flexible manufacturing?
  - Is it economical?

Figure IV-2. Issues for Products or Devices

- HIGH QUALITY REPRODUCIBLE, RELIABLE PRODUCTS
- ELIMINATION OF SCRAP AND RE-WORK
- REDUCED DEVELOPMENT TIME
- LOWER UNIT COST
- LOW COST OF OWNERSHIP OVER LIFETIME

Figure IV-3. Program Benefits